

SELFIELD LOSSES AND SELFIELD STABILITY
OF SUPERCONDUCTING WIRES
WITH LOW CONDUCTIVITY MATRIX MATERIAL

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Abstract

The influence of the normal material in a superconducting wire on the selffield losses has been investigated. The results show that the contribution of the normal material is considerable in the case of a highly conductive material like Cu. Measurements on wires with CuNi-material show no significant contribution of the normal material to the losses. In the latter case, however, special attention should be paid to stability. Measurements show that the obtainable maximum current under a.c. conditions obeys the adiabatic stability criterion rather well. The dependence of the maximum current amplitude on the critical current density and the diameter of the wire has been obtained. Wires with Al cores inside the NbTi filaments for better stabilization have also been investigated regarding maximum current and selffield losses.

Introduction

The low temperature department at Twente University is interested in constructing highly efficient superconducting transformers. Therefore special attention should be paid to the a.c. loss behaviour. Several commercially available superconducting wires have been investigated.

In transformers the magnetic induction is relatively small compared with d.c. applications. As a consequence the critical current density is rather high. Combined with the selffield (SF) effect (because of a.c. operation) this makes the superconductor unstable. The common way of increasing stability is to add highly conductive material to the superconductor. This, however, increases the losses as will be shown later. Other ways of stabilization have to be considered. A suggestion in literature^{1,2} (specially applied to reduce coupling losses in external a.c. fields, while maintaining stability) is to put a highly conductive core inside the filaments. A wire of this type has been tested under S.F. conditions. In the cases when selffields occur another possibility is to produce NbTi tubes with an Al-core inside. The behaviour of this wire is reported as well.

Method

The applied a.c. current is induced in a closed loop of the test-wire. The current is measured by means of a Rogowski pick-up coil. Voltage contacts across a straight part of the wire give the electric field at the surface of the wire.

Two ways of obtaining the loss have been used 1) by measuring with sinusoidal currents, an effective voltage can be obtained with a phase sensitive detector using the bandpass filter; 2) by using a LSI-11 computer,

$$\int_0^T V \cdot I \, dt$$

can be obtained in a direct way. In this case other current shapes, like a trapezoidal one, are possible. Using the latter one it is possible to obtain the critical current density from the voltage signal.

In both situations the compensation of the electric field component caused by the changing magnetic field of the wire is essential for the accuracy.

The maximum obtainable current amplitude is found by increasing the current until a quench occurs. In the case of fully stabilized wires, no quench due to flux-jumping is possible and the maximum current, equal to the critical current, can be derived from an increase in the losses as will be illustrated later. More details will be published elsewhere.

Theory

1. A.C. losses. The losses in superconducting wires under selffield conditions are well described by

$$P_H = \frac{\mu_0}{6\pi^2} \frac{I_0^3 f}{j_e R^2} \quad (1)$$

in the case of relatively low currents compared with the critical current (see ref. 3). Using a highly conductive outer layer of normal material for stabilization, the losses increase in first order approximation by

$$P_L = \frac{\pi}{3} \mu_0^2 \sigma \left(\frac{d}{R}\right)^3 I_0^2 f^2 \quad (2)$$

In the case of multifilamentary wire the contribution of the matrix to the selffield losses is

$$P_M = \frac{\mu_0^2}{384\pi} \frac{\sigma_e f^2 I_0^5}{R^4 j_e^3} \quad (3)$$

For available wires the last contribution is small compared with P_H and P_L .

2. Stability. Under adiabatic conditions the choice of the product $j_e R$ depends on material constants as

$$j_e R < \left(\frac{\pi^2 C T_0}{4\mu_0} \right)^{\frac{1}{2}} \quad (4)$$

Under selffield conditions this criterion depends on the current ratio $i = I_{\max}/I_C$.

$$j_e R < \left(\frac{8C T_0}{\mu_0} \right)^{\frac{1}{2}} \cdot f(i) \quad (5)$$

with

$$f(i) = \{-i^2 - 2i - 2 \ln(1-i)\}^{-\frac{1}{2}} \quad (6)$$

See Fig. 1. and ref. 4.

The following assumptions have been made:

- 1) Temperature distribution is taken as homogeneous;
 - 2) Heat capacity is taken to be constant as in (4).
- This model gives a conservative limit for stable operation. Calculations of Duchateau and Türck (ref. 5), taking into account heat conduction, illustrate that in the case of a highly conductive matrix this limit is at a higher level.

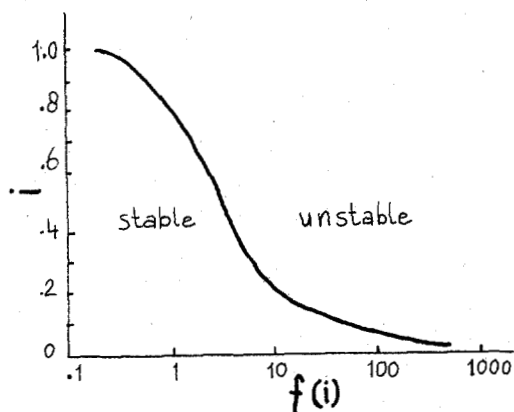


Fig. 1. Stable and unstable area in the case of the adiabatic selffield criterion for circular wires.

In general an unstable wire will carry a current corresponding to a point in the neighbourhood of the stability limit. The maximum obtainable current of an unstable wire can be calculated in this way.

Results

1. Measurements on NbTi multifilament wire with a CuNi matrix.

a). Dependence of stability on J_c . The test wire is A Supercon wire of $\phi .208$ mm, (see Table I). The current shape is sinusoidal. The loss measurements have been done with the phase sensitive detector at 80 Hz. This wire appears to obey formula (1) satisfactorily so that calculation of the critical current density from the loss measurements is possible (Fig. 2). In Fig. 3 the losses against external d.c. field for different current amplitudes are shown. The field direction has an angle of 45° with the wire axis. No minima occur under these conditions. While increasing the d.c. field the losses increase because of the reduction of the critical current density.

The small diameter of the filaments ensures that magnetization effects of the filaments are negligible ($B_p = 30$ mT). Also the selffield is relatively small compared with the used d.c. fields (0.1 - 0.2 T).

In Fig. 4 the maximum current amplitude against frequency is shown. The decrease beyond 10 Hz is probably caused by the temperature rise and its influence on j_c . At frequencies lower than 1 Hz the selffield is not complete, which sometimes results in higher currents. Noise on the power amplifier makes it difficult to determine the value with high accuracy.

In Fig. 5, equation (5) has been drawn together with the obtainable current against critical current density.

b. Dependence on diameter. Five wires of the same billet but drawn to .381, .178, .114, .089 and .076 mm have been investigated. The maximum obtainable currents are shown in Fig. 6 together with the commonly used $I_c = j_e \cdot \pi R^2$ and the curve calculated from equation (5).

For small diameters the wires are stable, i.e. the maximum current is equal to the critical current. This gives a possibility to determine j_c . This holds especially for lower frequencies (e.g. 4 Hz); for higher frequencies heat dissipation decreases stability. The obtained curve obeys the adiabatic criterion rather well.

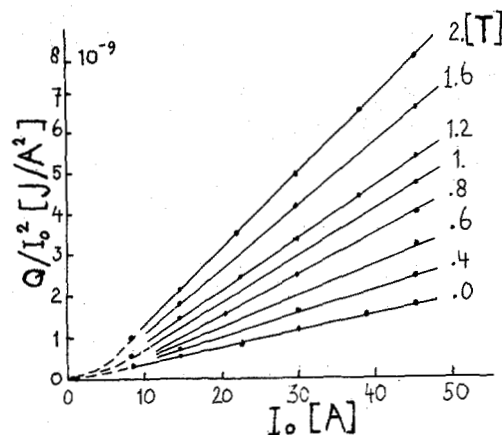


Fig. 2. S.F. loss of multifilamentary wire of NbTi in CuNi matrix with different applied d.c. fields.

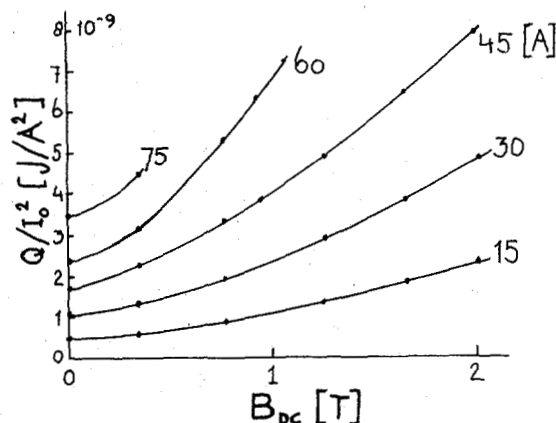


Fig. 3. S.F. loss of multifilamentary wire of NbTi in CuNi matrix against applied d.c. field with different current amplitudes.

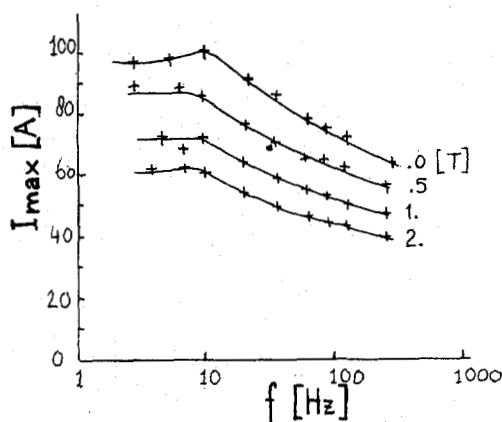


Fig. 4. Maximum obtainable current against frequency of a multifilamentary wire of NbTi in CuNi matrix with applied d.c. field.

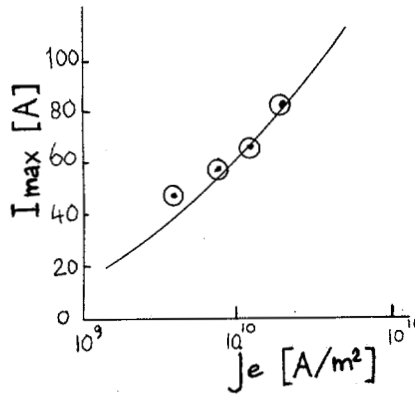


Fig. 5. Maximum obtainable current against critical current density under selffield conditions.

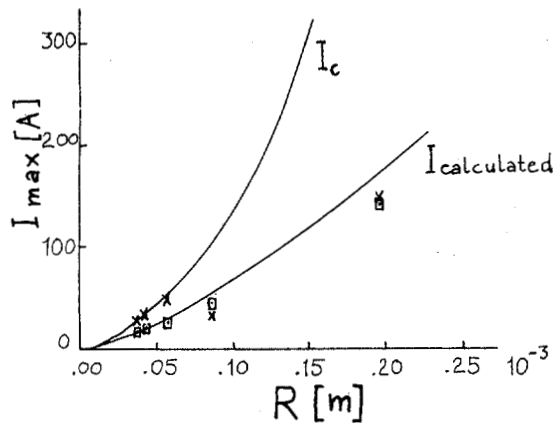


Fig. 6. Maximum obtainable current against wire radius $I_c = j_e \pi R^2$ and I_{cal} according to the theory.

2. Measurements on single core wire with and without a Cu outer layer.

The influence on the losses of a Cu outer layer for stabilization is illustrated in Fig. 7. In the case of low amplitudes the increase in losses is considerable. The increase of the maximum obtainable current however is also considerable, see Fig. 8.

In literature, the Cu is supposed to transfer the heat effectively to the helium and also to increase the heat capacity. A third effect is that the Cu layer carries part of the current after a flux jump has occurred. The Cu layer prevents flux entering after a sudden decrease of j_c by a temperature rise, so total flux inside the superconductor remains the same. Hence dissipation after a flux jump will be lower. The maximum current therefore will be higher than in a situation without a Cu layer.

3. Measurements on a wire with a highly conductive core inside a NbTi tube.

In this case a $\phi.450$ mm NbTi tube with a core of $\phi.225$ mm of pure Al has been tested. Some measurements with an extra Cu layer (necessary during processing; like extrusion and drawing) are included as well ($\phi.77$ mm).

In Fig. 9 the results of the loss measurements are shown. Interesting is that in both cases (with and without Cu) a smooth increase in losses exists. The loss behaviour changes and it is assumed that the flux front enters the normal core. A quench with the character of a flux jump does not occur.

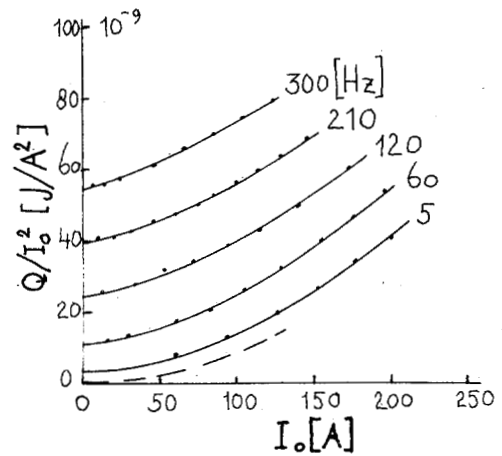


Fig. 7. S.F. losses of single core wire with Cu outer layer (solid line) and without Cu outer layer (dashed line).

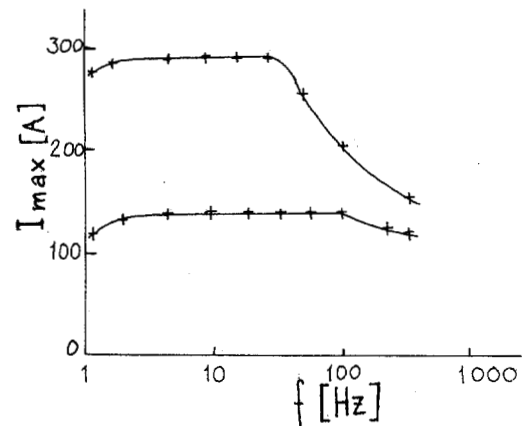


Fig. 8. Maximum current of single core wire with a Cu layer (upper) and without (lower).

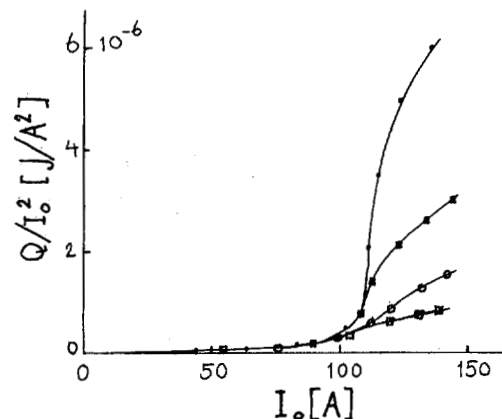


Fig. 9. S.F. losses of single tube wire of NbTi with an Al core inside. With a Cu layer (upper two) and without (lower two).

4. Measurements on wires with Al cores inside the filaments.

In Fig. 10 and 11 the selffield losses and the maximum a.c. current are shown. The radius of the wire is .4 mm. There are 54 filaments with $A_{al}/A_{sc} = 0.3$ and $\eta = 0.286$. The maximum current gives a magnetic induction at the surface of $B = .25$ T. Although this value is high for selffield applications no significant improvement of selffield stability is observed.

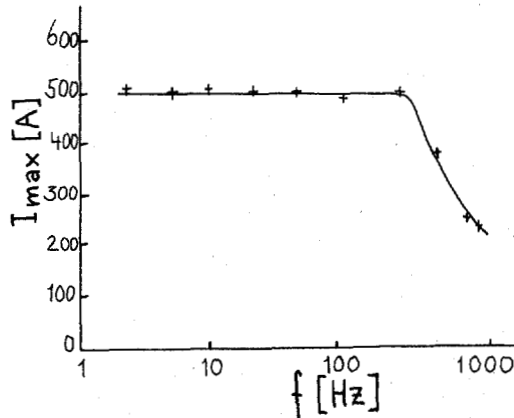


Fig. 10. Maximum obtainable current of a NbTi multifilamentary wire with low conductivity matrix and Al cores inside the filaments.

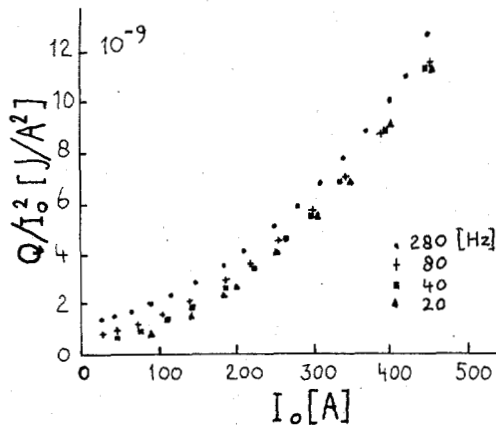


Fig. 11. S.F. losses of a NbTi wire with Al cores inside the filaments.

Conclusions

When using low conductivity matrix material to decrease the a.c. selffield losses, the a.c. selffield stability decreases as well. Most wires are unstable except wires with very small diameters ($< .1$ mm). An increase of stability can be obtained by using highly conductive material as a core inside the superconductor. The losses are not affected by this core.

Nomenclature

Q	J	Loss per cycle per unit length
P_H, P_L, P_M	W	Powerloss per unit length
$I_0; I_c$	A	Current amplitude; Critical current
f	s ⁻¹	frequency
$j_e; j_c$	A/m ²	ηj_c ; critical current density
R; d		Radius of the wire; thickness of the Cu layer
$\sigma; \sigma_e$	A/Vm	Conductivity; $(1-\eta)\sigma$
C_e	J/m ³ K	Heat capacity of whole wire
T_0	K	Difference between critical and bath temperature
λ		Superconductor/normal material ratio
η		Superconductor ratio
B; B_p	T	Magnetic induction; difference between induction in the centre and at the surface of the filament
A	m ²	Surface
i		I_0/I_c

Table I. Test wires

No.	ϕ [mm]	S.c.	Matrix	Fil.	λ
1a	.208	NbTi	CuNi	354	1.3
1b	.381	NbTi	CuNi	61	2.5
2	.50	NbTi	Cu	1	3.0
3	.45	NbTi	Al	1	0.25
4	.86	NbTi	Al5056*	54	2.5

* with Al inside the filaments: $A_{al}/A_{sc} = .3$

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